Springer Transactions in Civil and Environmental Engineering

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ISSN 2363-7633 ISSN 2363-7641 (electronic)
Springer Transactions in Civil and Environmental Engineering
ISBN 978-3-319-04812-3 ISBN 978-3-319-04813-0 (eBook)
DOI 10.1007/978-3-319-04813-0

Library of Congress Control Number: 2015933624

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media
(www.springer.com)

Introduction

Ground Penetrating Radar (GPR) is a safe, advanced, and non-invasive sensing technique that has several traditional and novel applications, sometimes standardised by national or international regulations. It can be effectively used for subsurface investigation, three-dimensional imaging of composite structures, and diagnostics affecting the whole life-cycle of civil engineering works.

The major GPR strengths, on which its success in the civil engineering field is based, are related to the non-destructiveness and non-intrusiveness of the surveys, notably lower costs compared to traditional methods, high-speed data acquisition, reliability and representativeness of measurements. The time needed for a survey is typically one order of magnitude shorter than with possible alternative technology; this results in obvious business benefits of reduced costs, together with limited or eliminated charges associated to restricting access of other activities to the investigated area. GPR provides significant, dense and accurate data; the resolution is higher, compared to competing geophysical technologies as seismic, transient electromagnetic, electrical and magnetic approaches. The main performance limitations occur in the presence of high-conductivity materials, such as clay or salt-contaminated soils, and in heterogeneous conditions causing complicated electromagnetic-scattering phenomena. Considerable expertise is necessary to effectively design and conduct a survey; moreover, the interpretation of radargrams is generally non-intuitive, thus specific competences are needed to enable measurements to be transformed into clear pictures and engineering decision-making data. We are confident that, thanks to the improvement and evolution of both hardware and software technologies, ground-penetrating radar will become an even more efficient, effective, extensively used and less-invasive technique in the near future.

Looking at the current interest of the scientific community, technicians and professionals all over the world, towards GPR and its civil engineering applications, it could seem that the history of this electromagnetic technique is very long. Then, it may sound odd that its origin is assumed in the first applications of the radio-wave propagation above and along the surface of the Earth that were developed about 60 years ago. The first use in the field of civil engineering is commonly considered to have taken place in Egypt and it was oriented to identify the water table depth: in 1956, El Said implemented a research programme, funded by the Egyptian National Research Council, for the geophysical prospection of underground water in the deserts. It is interesting to underline that the methodology adopted by El Said was essentially the same as is currently used to estimate the thickness of layers or the burial depth of targets. In particular, he used a continuous-wave transmitter to diffuse electromagnetic energy in the ground through an antenna laid on the soil surface. A radio receiver measured the wave reflected by the water table. The distance between receiver and transmitter was known. Following procedures nowadays still used, he calculated the depth of the table by measuring the time delay of the received wave.

The whole history of ground penetrating radar is intertwined with its various applications. A significant activity in the field of civil engineering started up in the 1960s and has become mature in the 1970s. Mines and underground deposit inspections were very frequent. Moreover, in the line of the lunar science missions, strong efforts were spent to improve new technologies that seemed very promising for the subsurface examination. Additional and promising uses were observed in archaeology and geology. The electrical characterisation of geological materials, as well as the relationships between electrical conductivity and dielectric polarisation, were topics of great interest in the research community. In the 1980s, the GPR borehole configuration was successfully proposed for the assessment of nuclear waste disposal sites. Starting from these experiences, the borehole configuration has become a relevant standard for hydrological studies of porous media. Another application, that is now likely the most financed, is mine detection for security and humanitarian purposes. In recent years, the GPR was proposed and successfully used for the localisation of people buried or trapped under snow or debris, aiding rescue activities in disaster scenarios such as avalanches, collapsed buildings and earthquakes.

In the civil engineering field, GPR is currently used for inspection, monitoring and design purposes. The detection of utilities and buried objects, as well as the surveying of road pavements, bridge decks, tunnels, and the measurement of moisture content in natural soils and manmade materials, are the main applications. In addition, interesting examples concerning the use of the ground penetrating radar in structural, geotechnical and railway engineering have to be mentioned.

This book is a deliverable of the COST (European COoperation in Science and Technology) Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar."

COST is the longest-running European (EU) framework supporting cooperation among scientists and researchers across Europe; founded in 1971, it has been confirmed in Horizon 2020. It contributes to reducing the fragmentation in EU research investments, building the European Research Area (ERA) and opening it to cooperation worldwide. It also aims at constituting a "bridge" towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe, and fostering the establishment of excellence in various key scientific domains. Gender balance and early-stage researchers are strategic priorities of this programme.

COST does not fund research itself, but provides support for networking activities carried out within Actions: these are bottom-up science and technology networks, centred around nationally funded research projects, with a 4-year duration and a minimum participation of five COST Countries. The Actions are active through a range of networking tools, such as meetings, workshops, conferences, training schools, short-term scientific missions, and dissemination activities; they are open to researchers and experts from universities, public and private research institutions, non-governmental organisations, industry, and small and medium-sized enterprises.

The Action TU1208 is running in the "Transport and Urban Development" COST domain; it started in April 2013 and focuses on the exchange of scientific-technical knowledge and experience of GPR techniques in civil engineering, aiming at promoting throughout Europe a more effective use of this inspection method. The ambitious and interdisciplinary project of the COST Action TU1208 is being developed within the frame of a unique approach based on the integrated contribution of university researchers, software developers, geophysicists, civil and electronic engineers, archaeologists, non-destructive testing equipment designers and producers, end users from private companies and stakeholders from public agencies. About 300 participants from 130 institutions in 28 COST Countries (Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Malta, Macedonia, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, UK) and a COST Cooperating State (Israel) have joined the Action. Partners from COST Near-Neighbour Countries (Albania, Armenia, Egypt, Jordan, Russia, Ukraine) and International Partner Countries (Australia, Philippines, Rwanda, United States of America) are participating, too. Applications from further Countries are currently under examination.

During the first year of activity, the partners worked on highlighting the advantages and limitations of the currently available equipment, surveying procedures, and electromagnetic/numerical methods for the interpretation of experimental data. Such studies led to a comprehensive assessment of the state of the art in the field of the civil engineering applications of GPR, and to the identification of open issues and gaps in knowledge and technology. The results of this wide and in-depth review activity were fruitfully discussed during Action's meetings and are presented in this book.

The organisation of the book reflects the scientific structure of the Action, which includes four Working Groups (WGs). In particular, the WG 1 of the COST Action TU1208 focuses on the design of innovative GPR equipment, the building of prototypes, the development of testing and calibration procedures, and the optimisation of new systems. The WG 2 deals with surveying of transport infrastructures and buildings, sensing of underground utilities and voids, testing of construction materials and estimation of soil water content. The WG 3 is developing accurate and fast electromagnetic scattering approaches for the characterisation of complex scenarios, inversion and imaging techniques, and data processing algorithms for the elaboration of GPR data collected during civil-engineering surveys. Finally, the WG 4 focuses on the applications of GPR outside from the civil engineering field, as well as on the combination of GPR with other non-destructive testing techniques.

The book is opened with the first chapter of Part I—"GPR Instrumentation"—authored by G. Manacorda et al. and entitled "Design of Advanced GPR Equipment for Civil Engineering Applications," where the main issues in designing ground penetrating radar equipment dedicated to civil engineering applications are described. A comprehensive review on the commonly available system architectures along with the main design challenges to build an effective tool are herein provided. Overall, the work mostly focuses on three major areas where solutions to technical challenges are nowadays more than ever needed, namely, radio-frequency system design, antenna design and data analysis.

The transmitting and receiving antennas are among the most critical parts of a ground penetrating radar, performing the essential functions of transferring electromagnetic energy to the surveyed scenario with the required pattern, bandwidth and efficiency, and receiving the energy scattered-reflected by the environment. For this reason, Part I is complemented with the chapter by L. Pajewski et al., entitled "Antennas for GPR Systems." This contribution offers a review on the antennas currently used in GPRs, suggesting ideas for their improvement, and resuming the numerical and experimental methods for their electromagnetic characterisation.

Part II of the book is entitled "GPR Surveying of Pavements, Bridges, Tunnels and Buildings; Underground Utility and Void Sensing." It includes five contributions on this topic.

The chapter authored by J. Stryk et al. is entitled "Innovative Inspection Procedures for Effective GPR Surveying of Critical Transport Infrastructures (Pavements, Bridges and Tunnels)." This work thoroughly reviews individual applications, which are currently in use, and outlines those that are still in the phase of research and verification. An overview on issues that need to be dealt with GPR is also addressed, to enable the larger applicability of this non-destructive method in critical transport infrastructures.

The following chapter is entitled "Inspection Procedures for Effective GPR Surveying of Buildings," by V. Pérez-Gracia and M. Solla. It focuses on the main achievements in surveying different types of buildings, on the software development for enhancing data interpretation and on laboratory studies that can be overall relevant for the analyses of complex scenarios. Open issues are also defined as a final conclusion, based on the revision of different works.

In their chapter "Inspection Procedures for Effective GPR Sensing and Mapping of Underground Utilities and Voids, with a Focus to Urban Areas," C. Plati and X. Dérobert present some studies showing the ground penetrating radar performances and limitations in locating and mapping objects such as pipes, drums, tanks, cables and underground features or in detecting subsurface voids related to subsidence and erosion of ground materials, from single-channel systems to the potential of multi-channel three-dimensional imaging and integrating systems. The Authors also discuss the importance of achieving cost-effective installations from the deployment of GPR prior to directional drilling for the prevention of damage to existing utilities.

L. Krysinski and J. Hugenschmidt authored the chapter "Effective GPR Inspection Procedures for Construction Materials and Structures," in which a review of approaches related to the assessment of construction details and material properties by using ground penetrating radar is presented. The analysis of the authors relies on the assessment of electromagnetic properties as a fundamental mean for understanding both materials physical properties and as an inherent part of any GPR structural study necessary for correcting uncalibrated electromagnetic parameters. Major directions of research along with some benefits and limits of different approaches are herein described.

To complete Part II of the book, the chapter by F. Tosti and E. Slob, entitled "Determination, by Using GPR, of the Volumetric Water Content in Structures, Substructures, Foundations and Soil," describes the use of several instruments and processing techniques for the evaluation of volumetric water content in concrete structures and unsaturated soils, at different investigation scales. Strength points and main drawbacks of the commonly used approaches for moisture sensing are discussed, relative to the most recent research studies on this issue. In addition, recently developed methods on this field of application are introduced.

Part III of the book is entitled "Electromagnetic Methods for Near-Field Scattering Problems by Buried Structures; Data Processing Techniques;" it includes overall four contributions on these issues

This part of the book is opened by the chapter "Methods for the Electromagnetic Forward Scattering by Buried Objects," written by C. Ponti, in which the usefulness in using dedicated tools for the solution of forward electromagnetic scattering by buried objects is outlined, with the main purpose of interpreting the GPR responses. A review on the most established approaches in the modelling of impulse radar systems, such as Finite-Difference Time Domain or space-time integral equations, is developed. Furthermore, the issue of implementing novel approaches to approximate the integral equations via series expansions with lower computational complexity, when adopting a Method of Moments discretisation, is addressed. The spectral-domain Cylindrical Wave Approach is presented.

In the following chapter, entitled "Development of Intrinsic Models for Describing Near-field Antenna Effects, Including Antenna-Medium Coupling, for Improved Radar Data Processing Using Full-Wave Inversion," A.P. Tran and S. Lambot deal with the proper description of antenna effects on GPR data and resume the methods that have been developed for this purpose. Traditional numerical methods are computationally expansive and often not able to provide an accurate reproduction of real measurements. The Authors thoroughly describe how intrinsic modelling approaches, through which radar antennas can be effectively described taking into account their fundamental properties, have demonstrated great promise for fast and accurate near-field radar antenna modelling in order to reliably estimate medium electrical properties.

In the chapter "GPR Imaging via Qualitative and Quantitative Approaches," I. Catapano et al. resume the issue of solving an inverse scattering problem, where a set of parameters describing the underground scenario must be retrieved starting from samples of the measured electromagnetic field. The authors provide an overview of different approaches and algorithms for both quantitative and qualitative buried scatterer reconstruction.

N. Economou et al. complete Part III of the book with a chapter on "GPR Data Processing Techniques," wherein the difficulties in automating data analysis are mainly addressed. In this regard, after providing the reader with a deep understanding of the state of the art and open issues in the field of GPR data processing techniques, the authors present an overview on noise suppression, deconvolution, migration, attribute analysis and classification techniques with a particular focus on data collected during civil engineering surveys.

This book is concluded with Part IV "Different Applications of GPR and Other Non-Destructive Testing Technologies in Civil Engineering," which includes four chapters.

The first contribution is entitled "Applications of GPR for Humanitarian Assistance and Security," by X. Núñez-Nieto et al. This chapter reviews a series of published works in the frame of the ground penetrating radar applications for humanitarian assistance and security, with a special reference to the detection of mines and unexploded ordnances. The location of underground spaces and the GPR use in rescue operations is also addressed, wherein its contribution in locating human remains or living victims in disaster areas is always more demanded. The authors analyse specific systems, methodologies and processing algorithms specifically developed for these applications.

The following chapter, entitled "Applications of GPR in Association with Other Non-Destructive Testing Methods in Surveying of Transport Infrastructures," written by M. Solla et al., reviews a compilation of works in the frame of the applications of GPR combined to other non-invasive methods in the evaluation of transport infrastructures. The authors demonstrate that these integrated approaches have significantly benefited the procedures for inspection and they successfully solved some of the limitations of traditional methods in monitoring roads and pavements, concrete and masonry structures, and tunnels.

The next chapter, entitled "Advanced Electric and Electromagnetic Methods for the Characterisation of Soil," by M. Van Meirvenne, deals with the detailed spatial characterisation of soil properties with different electric and electromagnetic methods, which is essential for the management of soil to provide all its functions and essential services to the environment. Electrical resistivity sensors, ground penetrating radar systems and electromagnetic induction sensors are herein thoroughly compared by outlining potential targets of each measurement technique, along with advantages and limitations. Despite the strengths of every type of sensing system, it is suggested by the author an increased integration of soil sensors into multi-sensor systems enabling their fused processing as a future challenge for enhancing the reliability of soil analyses.

The last chapter, entitled "Applications of radar systems in planetary sciences: an overview," by F. Tosti and L. Pajewski, focuses on the remarkable results and sophistication of radar systems achieved over the history in several planetary explorations, by dividing the treatment according to different planets and celestial bodies investigated.

We would like to thank very much the Authors of all the Chapters, for contributing to this book. We are also sincerely grateful to Springer, to Dr. Pierpaolo Riva, Springer Engineering and Applied Sciences Editor, and to the Springer Editorial Staff, for giving us the opportunity to publish this book, for their patience, suggestions and support, and for the efficient handling of the editorial process. Finally, we would like to thank COST for funding the Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar."

Andrea Benedetto
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Part I
GPR Instrumentation

Design of Advanced GPR Equipment for Civil Engineering Applications

Guido Manacorda, Raffaele Persico and Howard F. Scott

Abstract This chapter describes the issues to be addressed in the design of Ground Penetrating Radar equipment dedicated to civil engineering applications. Radar is well known for its ability to detect aircraft, ships, vehicles, birds, rainstorms and other above-ground objects. It relies for its operation on the transmission of electro-magnetic energy, usually in the form of a pulse, and the detection of the small amount of energy that is reflected from the target. The round-trip transit time of the pulse and its reflection provide range information on the target. The application of radar in the detection of buried objects is quite old; there are details of such work dating back to 1910, with the first pulsed experiments reported in 1926 when the depths of rock strata were determined by time-of-flight methods. The design of effective Ground Penetrating Radars requires solutions to technical challenges in three major areas:

- Radio Frequency system design.
- Antenna design.
- Data analysis.

Hence, this chapter reviews the commonly available GPR system architectures and summarises main design challenges to build an effective tool.

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A. Benedetto and L. Pajewski (eds.), *Civil Engineering Applications of Ground Penetrating Radar*, Springer Transactions in Civil and Environmental Engineering, DOI 10.1007/978-3-319-04813-0_1

1 Introduction

The use of Ground Penetrating Radars (GPRs) in civil engineering is well established and there are several applications where it is currently utilised; they include the location of buried services, the detection voids or cavities, locating steel reinforcement in concrete, geotechnical foundation investigations, as well as archaeological, environmental and hydro-geological surveys.

The main applications of GPR to transportation infrastructures generally include measuring the thickness of pavement layers, detecting voids beneath layers, detecting and locating reinforcing bars, inspecting pavement structure, and mapping of the underground utilities.

Ground Penetrating Radars are designed to probe up to a few metres into the ground through material that is, usually, non-homogenous and, unlike free-space, strongly absorbs radar signals. The frequency range that has been found to be useful for such an application lies within the limits of 100 MHz to 2 GHz.

Requirements for civil engineering applications differ, depending upon the application, and each one imposes a particular set of constraints on the design of an effective GPR. For example, the majority of buried plant is within 1.5–2 m of the ground surface, but it may have a wide variation in its size, may be metallic or non-metallic, may be in close proximity to other plant and may be buried in any one of a wide range of soil types, with implications for large differences in both the absorption and the velocity of propagation of electro-magnetic waves, and consequent effects upon GPR performance. For this application, the most important performance criterion is depth of penetration, with resolution (the ability to distinguish between closely space objects), whilst being important, is a secondary consideration.

On the other hand, surveys of concrete or asphalt pavements requires very high resolution for accurately measuring the thickness of layers composing roadways or the runways; the same applies to the assessment of bridge decks where GPR signals can be analysed to detect potentially corroded areas.

Performance characteristics of GPRs are also often affected by ground conditions that may vary rapidly within the area of a radar survey where, for example, variations in water content can be crucial and, particularly in urban areas, where there could be imported backfill of inconsistent quality. Consequently, it can sometimes be problematic to achieve both adequate penetration of the radar energy and good resolution, and some design compromises may have to be accepted.

In addition, a further issue concerns the interpretation of GPR data, which is not trivial in many situations; in this respect, the latest developments in GPR are oriented towards the design of equipment featuring real-time 3D high resolution images of surveyed areas.

Images, such as that shown in Fig. 1 can easily be understood even by an unskilled operator; however, this visualisation improvement can be effective only if the GPR performs well in terms of signal quality and detection range; in fact, if the received signal is too weak, as would be the case in wet, muddy ground, enhanced graphics software will solve neither the basic signal problem nor the detection performance.

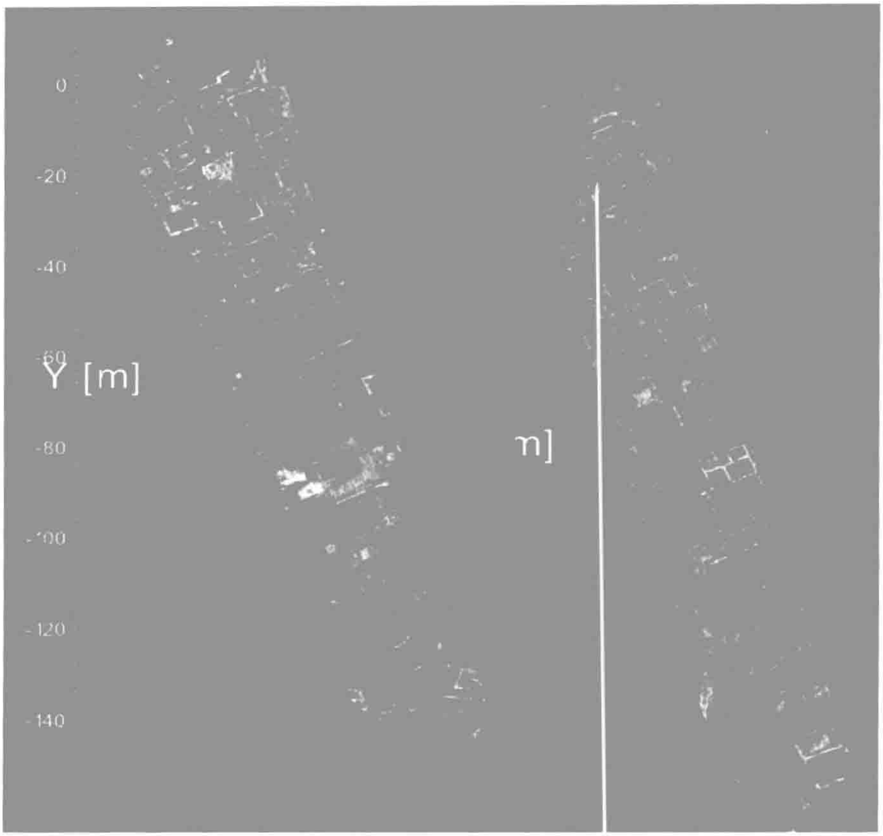

Fig. 1 High resolution GPR image of the archaeological site of Empúries (Spain) (Courtesy of Geostudi Astier—Italy)

Consequently, the design of high performance equipment is a complex but fascinating task for engineers and researchers as it involves a wide range of expertise such as electromagnetic wave propagation in media, antenna technology, radar design and electronics as well as advanced signal processing techniques and computer graphics.

2 The Radio Frequency System

2.1 Introduction

The purpose of the Radio Frequency (RF) system is:

- To generate an electrical signal of appropriate power level, frequency range and spectral characteristics, and to apply it to the transmit antenna.
- To process energy collected by the receive antenna into a form suitable for data analysis.